Perspective Report Series 5

BASIC BUILDING BLOCKS BEGAN (...) BIG BANG

(An Overview of the Physics of Elementary Particles)

A. N. MITRA

Department of Physics, University of Delhi,
Delhi

GOLDEN JUBILEE PUBLICATION

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1. Introduction

Three stages of Elementarity

If there is any truth at all in the Big Bang theory of the universe, a quest for the ultimate structure of matter should logically be traced all the way to that particular Moment. However, the path is long and arduous, and almost entirely buried in terrestrial and cosmological signatures. Indeed the debris is so deep that (except perhaps for the divine insights of the Great Seers through the Ages which would have to trancend physical description any way) the physical concept of an elementary particle was confined to the various elements or atoms as the basic units till the end of the 19th Century. Even this knowledge (or rather information) was highly empirical, until Mendeleyev injected a profound order in their description by arranging them in the Periodic Table. This was a landmark in the understanding of matter, and heralded the birth of the group concept which was to find an ever increasing degree of involvement in the successive stages of unfolding of the mysteries of Creation throughout the next century (much like the process of peeling the successive layers of onion skins).

The regularities that were implied in the Periodic Table supported by a vast array of spectroscopic data, were eventually 'understood' half a century later (in the 1910's) through the realization, within the theoretical framework of quantum mechanics, that the atom was *not* an elementary particle after all, but rather a *composite* object, with electrons (e) orbiting around a central heavy nucleus (with linear dimensions 10,000 times smaller than the atom's) in well defined 'shells' specified by four distinct quantum numbers, in accordance with the Pauli Exclusion Principle (1925)[1]. The same theoretical framework provided, without extra charge, a natural understanding of molecular bonds and the diverse chemical properties of matter in an integrated fashion.

Compositeness of the atom merely represented the *first stage* in the unfolding of the strucure of matter, for as it turned out during the next half a century of research, at least two more stages had already been reached, with strong speculations about the *fourth stage* (?) fast gaining currency in the 1980's. The *second stage* was the demonstration of compositeness of the atomic nucleus with the discovery (1932)[2] of the *neutron* which is electrically neutral and yet was found to be a basic constituent of the atomic nucleus (where the entire mass is concentrated), on par with the *proton*. Again, a qualitatively common feature of nuclear compositeness with that at the atomic level turned out to be 'shell' structure, though with important differences in details. Indeed, in contrast to atomic spectra, the observational features of nuclear spectroscopy seemed to exhibit a striking resemblance to molecular spectra (rotational and vibrational, though on a vastly different energy scale (ten million fold bigger on the average). Interpreted literally, this would be taken to suggest that the nuclear constituents, or 'nucleons' (the proton and the neutron), play a very similar role in shaping nuclear structure to what atoms do in determining molecular structure (with their electronic degrees of freedom energetically suppressed so that they behave effectively like elementary constituents in this respect).

The *third stage* in the hierarchy of elementarity had been reached by the early sixties mostly through experimental discoveries, resulting in a two-fold proliferation of nucleon-like particles, (a) the so-called "strange" particles first observed in cosmic rays and subsequently produced in high energy accelerators, and (b) short-lived nucleonic states or 'resonances' produced by the bombardment of pi-meson beams on proton targets in the laboratory.

A word about the 'pi-meson' (which has entered our narrative for the first time at this stage) is in order. Just as the quanta of electromagnetic radiation—the *photons*—are ultimately responsible for atomic and molecular structure by mediating the coulomb force (in an effective action-at-a-distance sense) between any two charged particles, in much the same way it was conjectured by Yukawa (1935)[3] that the nucleons must be held together by short-range forces (to account for the much smaller dimensions of the nucleus) mediated by the so-called 'heavy quanta' or *mesons*. The rest mass of these quanta could be estimated to be about 200-300 times heavier than the electron, using the celebrated Uncertainty Principle of Heisenberg (1925)[4]. The subsequent identification of such a particle named the 'pi-meson' in cosmic rays (1947)[5] was a great triumph for the heavy quantum[6] rejected on the ground that it did not exhibit the desired (strong) interaction properties expected of a 'meson' as a cementing bond for the nucleons. In the fifties and early sixties, the pi-meson (or pion) soon found its (a) 'strange meson partners (kaon) in cosmic rays and (b) many short-lived meson excited states (meson resonances) produced in the laboratory by energetic pion beams, in parallel with the corresponding nucleon (or baryon)—like proliferations described above.

By the early sixties, mostly through experimental developments, the number of nucleon- and pion-like particles had reached alarming enough proportions (300) to warrant serious doubts on their individual claims to elementarity, even as generalized nuclear constituents which we shall collectively call *hadrons* (baryons and mesons) in what follows. Indeed, the numerical situation in respect of these hadrons would have been worse than the corresponding 'atomic' situation a hundred years earlier, but for certain Mendeleyev-like efforts[7] (during this period of turmoil) to bring in some 'order' in their description, using the tools of group theory[8]. History seemed to be repeating itself with an uncanny precision, when a solution came in sight shortly afterwards, through the revolutionaly proposal of Gell-Mann and Zweig (1964)[9], according to which these hadrons themselves were doublet and triplet composites of more elementary constituents, termed *quarks* (q). Indeed, only three varieties or 'flavours' named up, down, strange (u, d, s,) of these entities (q), together with their *antiparticles* ($\bar{q} = \bar{u}, \bar{d}, \bar{s}$), proved adequate for the description of all the 300-odd hadrons and their resonances as quantum mechanical two and three body systems (meson $= q\bar{q}$, baryon $= qqq$), much like the atomic and nuclear states are expressible in terms of electronic and nucleonic levels.

2. Leptons Quarks and Their Interactions

This remarkable development marked the *third stage* in the structural hierarchy of matter, but this picture would be incomplete without a brief parallel mention of the *lepton* sector. To describe a lepton, it is first necessary to record a fourfold observable classification of forces viz., electromagnetic (e. m.), strong-nuclear, weak-nuclear and gravitational, which govern particle interactions of different kinds. Of these e.m. and strong interactions have already been encountered at the atomic and nuclear levels respectively, while gravity is observationally the most tangible, yet conceptually perhaps the most baffling of all. The *Weak* nuclear force underlies, among other things, the phenomenon of nuclear β-decay whose experimental features of missing energy and angular momentum had led Pauli (1934) to introduce the theoretical concept of the elusive *neutrino* ((a massless, chargeless particle which can travel thousands of miles unnoticed) to accompany the β-particle (electron). Its existence as a partner (ν_e) of the electron (e) was experimentally confirmed later (1956)[10].

In a similar way, the muon (μ) which had proved a misfit[6] as a Yukawa-meson, turned out to have properties identical to those of the electron, except for being about 200 times heavier. In particular it participates in weak and e. m. interactions, just like the electron does and has a distinct neutrino partner ν_μ of its own. Neither the electron nor the nuon (and their associated neutrinos) exhibit strong interactions, but only weak and e.m. Such particles have been given the generic name of *leptons* (possessing associated neutrinos) which have so far maintained their elementarity on par with quarks (up to the 'third stage', that is). A third lepton, the tau (τ) which is 17 times heavier than the muon, was discovered a few years ago[11]. but its associated neutrino ν_τ is still awaited.

As a parallel development, two more quark flavours, but much heavier than the earlier three (u, d, s), were discovered in the seventies. These have been named 'charm' (c)[12] and 'beauty' (b)[13]. A sixth one, named the 'top' (t) in advance, is anxiously awaited on certain theoretical grounds which are in many ways reminiscent of the Mendeleyevian intuition — now at its *third stage* —, but of course with appropriate sophistication. Each of these quarks is supposed to possess *three* distinct *color*[14] charges (R, G, B) — a new degree of freedom — over and above a fractional electric charge $\left(\frac{2e}{3} \text{ or } -\frac{e}{3}\right)$. The Mendeleyev periodic table at this third stage of elementarity may now be arranged for quarks and leptons by generations as in table 1.

TABLE 1 : *Three Generations of quarks and leptons*

	Quark (R, G, B)		*Lepton* (*neutrino*)	
I	$u\left(\frac{2}{3}\right)$	$d\left(-\frac{1}{3}\right)$	$e^-(-1)$	$\nu_e\,(0)$
II	$c\left(\frac{2}{3}\right)$	$s\left(-\frac{1}{3}\right)$	$\mu^-(-1)$	$\nu_\mu\,(0)$
III	(?) $t\left(\frac{2}{3}\right)$	$b\left(-\frac{1}{3}\right)$	$\tau^-(-1)$	$(\nu_\tau)\,(0)$

Their electric charges, in units of the proton charge, are shown against each. Each of these particles has a corresponding *antiparticle* with reversed signs for electric and color charges.

Before ending this section a few words are in order in respect of the color charges of quarks, since such charges are alone responsible for their *strong* interactions (while their weak and e. m. interactions are exactly analogous to those of leptons). The strong interaction among color charges is mediated by a new (non-abelian) kind of field[15] the color carrying *gluon* field — in much the same way as the e. m. interaction or ordinary charges is mediated by the *photon* (e.m.) field. The gluon field operating at the quark level[16] now replaces the old concept of the Yukawa-meson as the mediator of the strong interaction among nucleons at the nuclear level.

This is highly satisfying in view of the (hindsight) knowledge of compositeness of both the Yukawa meson[3] and the nucleon, a major factor which could not possibly have been taken into account in the (then elementary particle) description of the 1930's. Indeed, the analogy between the electronic structure of atoms and the quark structure of hadrons is now much closer than had been the case with the nucleonic structure of nuclei (which, it may be recalled, had exhibited a closer similarity with the atomic structure ofmolecules)[17]. This last feature is particularly noticeable from the spectroscopy of *heavy* quatkonia ($c\bar{c}$, $\bar{b}b$ systems) which exhibits energy levels strongly resembling hydrogen-like spectra. (this coulomb-like feature disappears for *light* quark spectroscopy which is dominated by a non-coulombic long distance interaction). Any deeper significance of this purely empirical observation of spectroscopic similarity of successively alternating composite structures, viz

$$\begin{tikzcd}
\text{molecules} \arrow[rr, leftrightarrow, bend right] & \text{atoms} \arrow[rr, leftrightarrow, bend left] & \text{nuclei} & \text{hadrons}
\end{tikzcd}$$

is obviously a matter of great physical interest.

Finally the weak-nuclear interaction which had long been suspected to be mediated by an appropriate vector field[18] akin to the e.m. field governing the interaction of ordinary charged particles (and to the gluon field believed to be responsible for the strong interaction among quarks possessing 'color-charge') has indeed turned out to have just the right kind of vechicle desired by the theory as the carrier of still another type of 'charges' (flavour) which are possessed by both leptons and quarks. This idea which was proposed in the 'correct' form only 16 years ago* (Weinberg 1967, Salam 1968)[19] after two decades of theoretical debate has very recently found dramatic experimental confirmation[20] within this very year (1983) through the discovery of the massive $W^{\pm}$, Z^0 bosons in CERN's proton-antiproton collider at just the right masses (~100 times the proton mass) predicted by the theory.

3. Theoretical Foundations

So far we have outlined an emperical description of the successive stages of elementarity, resulting in the lepton-quark hierarchy in terms of the fundamental fields mediating their mutual interactions. What are the basic principles on which this edifice stands? These principles which have evolved through certain landmark developments in theoretical physics during this century, have had a direct bearing on current ideas on elementary particle structures *and* their interactions. The following is a partial list of the more important theoretical ingredients :

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* The Salam-Weinberg theory which unifies the e.m. and weak interactions through the gauge principle, naturally incorporates the chiral principle underlying the celebrated V−A theory of Sudarshan and Marshak, as well as of Feynman and Gell-Mann, which had been proposed in the late fifties as novel formulation of the precise mechanism (100% violation) through which the revolutionary Lee-Yang idea of parity violation in weak interactions was to find concrete expression.

(a) Two "classes" of particles : Bosons and Fermions.
(b) Concept of Antimatter.
(c) Generalized "charges" *and* their conservation.
(d) Gauge fields as force media and charge carriers.
(e) Spontaneous Symmetry Breaking (SSB) : massive gauge fields.
(f) The principle of unification of forces.
(g) Renormalizability of observables.

The discussion to follow is based on the (intangible) role of 'symmetry' which underlies all physical laws. Indeed this word is so basic to our language that instead of attempting a formal defiinition, it is safer to make judicious use of it in context, as a possible means of conveying its meaning to the reader.

3.1 *The Electromagnetic Field and QED : An Ideal Theory*

The last century saw two major landmarks in physics : (A) the Mendeleyev classification of elements and (B) Maxwell's celebrated Electromagnetic Theory of light. Just as the former had shown the way to bring *order* through the use of group structures in the understanding of particle properties, the latter was in many ways to serve as a perfect model for the basic qualities needed for a profound dynamical theory of to-day. Indeed, Maxwell's theory, by its emphasis on the underlying *unity* behind electricity and magnetism (hitherto considered as quite distinct phenomena) through the concept of a common electromagnetic *field*, already had the germs of several of the theoretical ingredients listed above, especially (a), (c), (d) and (g), as was to be revealed on different occasions in the past few decades. This theory not only turned out to be in the fullest harmony with Einstein's theory of relativity but the e.m. field was also the first to receive a renewed "particle" (radiation quantum) interpretation at the hands of Plank and Einstein (two centuries after Newton). Again, even before quantum mechanics took formal shape at the hands of Heisenberg (1927)[21], Schrodinger (1926)[22] and Dirac (1928)[23], one of its basic theoretical ingredients, viz., the "principle of indistinguishability" (of particles of a certain kind) had been established through the *photon* concept. This was the celebrated paper of S. N. Bose (1924)[24] in which he had advocated a new form of counting of quantum states for truly indistinguishable particles, a revolutionaly concept which drew enstant endorsement from Einstein. This marked the birth of the *BOSON* (a class of particles obeying the quantum statistics of Bose-Einstein) with the photon as its first non-trivial example.

With the rapid development of the principles and mathematical techniques of quantum field theory beginning with the thirties, the interaction of the Maxwelleian (e.m.) field with matter began to be understood in a new light. Indeed, the structure of the interaction was found to be so universal as to respect "gauge invariance". The basic idea can be described as follows, without going into technicalities. In order to conserve the total "charge" in the universe, it is necessary that all particles (electrons, protons, quarks,...) possessing the attribute of charge must couple to the e.m. field in a certain self-consistent manner such that the equations of motion of the *coupled* e.m. and matter fields remain invariant under simultaneous *gauge* transformations of the respective fields. For a rough understanding of such transformations, the fields must first be regarded as generalized coordinates in a much bigger (Hilbert) space on which 'gauge' transformations are supposed to act, in much the same way as Lorentz transormations act on ordinary space-time coordinates. *Invariance* under gauge transformations—which leads to conservation of charge—is a kind of "symmetry" more specialized than (but not different in spirit from) say, translational invariance (which leads to the conservation of 4-momentum) or rotational invariance (which gives rise to the conservation of angular momentum). That the e.m. field of Maxwell's imagination already possess the remarkable property of gauge-invariant coupling to all forms of electrically charged matter, thus automatically ensuring the conservation of total charge, lends *this* field a unique position in the curriculum of quantum field theory. The gauge point of view gives a new meaning to the entity called "charge" not only as a measure of the force between charged particles, but also as something that is *strictly conserved* as a result of its universal coupling to a "gauge field" of which the photon is once again the first non-trivial example.

Now the photon field would not have qualified for this unique title, had it not been for its massless character—an essential prerequisite for gauge invariance for the combined "Action" for the e.m. and matter fields. These developments gave rise to the modern theory of "quantum electrodynamics" (QED) developed by Tomonoga[25], Schwinger[26] and Feynman[27] (and interpreted by Dyson[28]), which apart from its spectacular experimental success in predicting the effect of electromagnetic interactions to 1 in 10^{12} accuracy, was found to possess yet another theoretical virtue—Renormalizability[28], a property which ensures infinity—free calculation of physical effects to any arbitrary order through suitable redefinitions of the electron mass and charge.

For all these reasons, the e.m. field has all along occupied a unique position in quantum field theory. Indeed all attempts at the construction of other interacting field theories during the second half of the present century have been patterned after the QED, keeping in view its fundamental characteristics. It is a *massless, vector* (boson), field which couples to all charged currents in a *gauge-invariant* manner and makes infinity-free predictions through the *renormalizability* property[28]. In this sense it is a universal carrier of electric charge, but does *not* possess any charge of its own. (Subsequently we shall come across a more general kind of "charge" which is also possessed by the carrier).

3.2 *Boson-Fermion Classification*

Before discussing the generalization of QED to other forms of gauge field theories as carriers of more general forms of physical attributes akin to the electric charge, let us digress briefly on two other characteristics of particles and fields in general viz (1) their boson-fermion character and (2) existence of anti-particles (or antifields). According to the Principle of Indistinguishability (which arose out of the new counting proposal of Bose)[24], the wave function of a set of truly identical particles must be *totally symmetric* w.r.t. to an interchange of the labels of any two of them. The *photon* was the first non-trivial example of this principle. Thus the 'wavefunction' for an *n*-photon state, specified by their respective *momenta* and states of polarization (or spin), should have this property. For any other class of identical particles whose *intrinsic* angular momentum or *spin* is an *integral* multiple of Planck's constant ($\hbar$), the corresponding wave function must be totally symmetric. There is another class of (identical) particles—those whose intrinsic angular momentum or *spin* is half-integral (in units of $\hbar$)-which obey a complementary symmetry, viz., their wave function must be totally *antisymmetric* w.r.t. to the interchange of any two particle labels. The antisymmetry property automatically ensures that such particles must obey Pauli's Exclusion Principle (since their wave function would vanish when any two particles with identical quantum numbers occupy the same position in space). The counting rule for this second type of particles was given by Fermi[29] and Dirac[23] with appropriate modifications in the Bose-Einstein rule. The electron whose spin is $1/2\ \hbar$, was the first non-trivial example of second type.

All particles in the Universe whether elementary or composite, have been found to belong to one or the two classes (1) *BOSONS* which exhibit integral spin and (2) *FERMIONS* which have half-integral spin. No exceptions to this rule have been found so far, *provided* all possible degrees of freedom are taken into account. Examples of Bosons are photon, alpha-particle, pi-meson, W-boson and gluon. Typical Fermions are electron, nucleon, triton, neutrino and quarks. It was later shown (again by Pauli) that the boson-fermion classification can be effectively derived from the very foundations of quantum field theory under rather general conditions (Lorentz invariance, causality and locality of basic field operators) which have generally been taken as almost axiomatic. (However, in recent years, a new symmetry between Boson and Fermion systems has been discovered which threatens to erase the distinction—see Sec. 10).

4. Anti-Matter

The present century began with a twin revolution in the laws of physics, Relativity (for fast moving objects) on the one hand and Quantum Theory (for 'small' objects) on the other. Each of these theories couldbe separately formulated in a consistent manner within their respective physical premises. Thus the Newtonian equations admitted of relativistic generalizations for fast-moving particles as long as the latter were not too small for quantum effects to be important. Likewise, the Hamiltonian equations of motion (an alternative mathematical form of the Newtonian equations, but with identical physical content) were shown to be adaptable to the Heisenberg form of quantum mechanics (or the alternative Schrödinger form), again in a fully self-consistent manner, when the particle under study was 'small' enough to invalidate the classical description but *not* 'fast' enough to require a simultaneous relativistic treatment. An entirely different scenario emerges, however, when an attempt is made to describe the motion of small and fast-moving particles since this would now require a combination of both these principles. This is what Dirac tried to do, and when he finally succeeded in giving a mathematically consistent formalism for the *relativistic quantum mechanics* of an electron, (one which left little to be desired in terms of its spectacular experimental success), he nevertheless came up with the surprising conclusion of the existence of the *antiparticle*—the positron—as a necessary consequence of the theory. What should be its experimental signatures ? It should be an exact replica of the electron in terms of mass and spin, *opposite signs* for its charge, magnetic moment and lepton number, as a result of which its contact with an electron will lead to the simultaneous destruction of both as particles, with the entire mass converted into energy (Photons), in accordance with Einstein's mass-energy relation. Experimental confirmation of this startling prediction came soon afterwards (1932)[30], thus strengthening a natural belief in the existence of antiparticles of *all* types of fermions-proton, neutron, neutrino and all that. That all these 'expected' antiparticles with the right properties were experimentally identified in the succeeding decades constitutes a non-trivial confirmation for the physical soundness of the Dirac theory.

According to the theory, quarks should have their antiparticles too. Here there is a new problem as it may be argued that since 'free" quarks have themselves not been "seen" explicitly (in the sense of most other particles) even two decades after their postulation, it may be a luxury to ask for their antiparticles. On the other hand, unobservability of 'free' quarks has not prevented their deeper and deeper involvement in hadron physics, so much so that this question is no longer considered 'relevant' to theory. Rather (making a virtue out of a necessity), quarks (q) are thought to be *permanently confined* inside their respective hadrons through the *color* interaction (to be discussed below), and that only their *flavours* (u, d, s,...) are supposed to have external manifestations. In this respect, antiquarks ($\bar{q}$) have not proved more elusive than their particle counterparts (quarks). Indeed for quarks, the signatures (if any) of particle versus antiparticle have proved more symmetrical than for most other (visible) fermions. The signatures of both are highly indirect, but noticed always in pairs, such as in the J/ψ particle ($\bar{c}$)[12] or the Upsilon ($b\bar{b}$) meson[13] whose net flavour contents are zero (by virtue of equal and opposite contributions from the quarks and the antiquark). A more direct test for their (simultaneous) 'visibility' perhaps lies in the prediction of quark-antiquark pair production, with the two members going out in *opposite* directions, in an electron-positron collider*. Events of this kind, were first observed in the PETRA[32] (at DESY) in 1978-79, with two "Jets" going out in opposite directions for short distances before "hadronization", as expected of a quark-antiquark pair according to theoretical calculations.

Prediction of antimatter as a strictly logical consequence of the theory contained an important lesson for the very logic of physics : A theoretical attempt to synthesize two distinct principles (quantum theory and relativity) had to satisfy the exacting demands of mathematical self-consistency, necessitating the introduction of an entirely new concept, which was to be so convincingly confirmed by experiment.

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* The electron — position e^+e^- collider which is an extremely powerful tool in high energy physics is based on the process of e^+e^- scattering, termed "Bhabha Scattering" after H J Bhabha (1935)[31] who first recognized the importance of e^+e^- annihilation as a basic contributor to this process on par with scattering via the exchange of photon.

A second lesson from the Dirac theory is the following. It should be impossible to have a relativistic quantum theory of a *single* particle (the electron), since its antiparticle must also come into the picture. It is only for a *field* (consisting of an infinite number of quanta) that a self-consistent formulation with both the principles (quantum theory and relativity) incorporated becomes possible[33]. This lesson immediately led to the realization that the antiparticle concept could not be a monopoly of fermions only — it must apply to bosons as well[34]. Unfortunately the photon is not a very good example of this concept, since there is no observabile attribute like "charge" that can distinguish it from an 'anti-photon'. In other words, *a photon is its own antiparticle.* However when a boson has an observable physical attribute, such as electric *charge* or *strangeness,* its anti-boson must be a distinct object. Examples of such boson pairs are

$$\pi^+ \leftrightarrow \pi^- ;\ K^+ \leftrightarrow K^-,\ K^0 \leftrightarrow \bar{K}^0;\ W^+ \leftrightarrow W^- \qquad \ldots(1)$$

On the other hand, the following examples show that certain bosons are their own antibosons :

$$\gamma = \bar{\gamma},\ Z^0 = \bar{Z}^0;\ \pi^0 = \bar{\pi}^0;\ (\phi, \Psi) = (\bar{\phi}, \bar{\Psi}) \qquad \ldots(2)$$

How about the gluons—the carriers of color ? Since quarks have color, antiquarks must possess *negative* color ($\bar{R}$. $\bar{G}$, $\bar{B}$) having characteristics exactly opposite to the color triplet (R, G, B). Since gluons are supposed to mediate interaction between all possible colored pairs, ($q\,\bar{q}$), ($q\,q$) and $\bar{q}\,\bar{q}$), they must also carry quantum numbers corresponding to *color-transitions,* e. g., $R \rightarrow G$, $R \rightarrow B$, apart from "colorless" transitions such as $R \rightarrow R$. In other words gluons must exhibit a rich color structure so that a particular gluon-state must in general be distinct, in terms of color content, from the corresponding antigluon-state. This necessitates a generalization of the concept of charge.

5. Non Abelian Charges : Isospin and Flavour

The simplest generalization of the concept of charge comes from the example of the nucleon which may be thought to exist in two distinct charge states (p, n) much like the two spin states (↑ , ↓) of an electron. This analogy gave rise to the concept of isospin, a legitimate degree of freedom analogous to ordinary spin[35], but defined in an altogether different space termed charge or isospin space—spanned by two abstract entities resembling the (p, n) pair. In formal language, the symmetry group is SU (2) whose representations are determined by the algebra of angular momentum (or spin). Just as in the absence of a preferred direction in space, the angular momentum is a constant of motion (rotational) symmetry), the isotropy of charge space would imply the conservation of isospin. Strong interactions at the hadronic and quark levels indeed respect this symmetry, as evidenced by the near equality of masses within each of the following typical isospin multiplets :

$$(p, n)\ ;\ (\pi^+\ \pi^0\ \pi^-);\ (K^+\ K^0);\ (\Sigma^+\Sigma^0\Sigma^-);\ (K^0\ K^-) \qquad \ldots(3)$$

The small differences are due to the violation of this symmetry by the e.m. field which singles out a preferred direction in isospin space and respects symmetry only w. r. t. that direction ; this fact corresponds to conservation of electric charge only. Weak interaction violates isospin symmetry in a bigger way, as seen from the rather large mass differences within the following multiplets :

$$(e^-, \nu_e);\ (\mu^-, \nu_\mu);\ (e^-, \bar{\nu}_e)\ ;\ (W^+, Z^0, W^-) \qquad \ldots(4)$$

Neverthelss, both e.m. and weak interactions (and of course the strong one) respect another (more general) symmetry[30] according to which a particle and its antiparticle must have identical masses. A few examples of this symmetry (CPT invariance) are:

$$m\,(\pi^+) = m\,(\pi^-);\ m\,(K^+) = mK^-,\ m\,(e^+) = m\,(e^-) \quad \ldots(5)$$

Isospin is the simplest manifestation of flavour. At the quark level it shows up through the SU (2) doublets (u,d), (c, s) and (t, b) of table 1. In a similar way the weak isospin doublets (e, ν_e), (μ, ν_μ), (τ, ν_τ) of table 1 exhibit the corresponding flavour SU (2) group in the lepton sector. However, the problem of understanding the group structure (if any) for the 3 successive generations (I, II, III) of flavour SU (2), as exhibited in table 1 for both quark and lepton sectors still remains unsolved. In particular there is no consensus yet on the question of whether the three-tier 'generation' structure is a manifestation of a new kind of symmetry (hence a new kind of "charge"), or is a pointer to still another level of elementarity (a question already raised at the beginning of Sec 2). According to the guage principle, the W and Z^0 bosons (the mediators of the weak interaction) are the carriers of flavour charge, just as the photon is the carrier of electric charge. In formal language, the latter field corresponds to the single parameter gauge group u (1) which is abelian, while the former make up the triplet representation $W^+\ W^-\ Z^0$) of the gauge group SU (2) which is non-abelian. In contrast to the case of the e.m. field (which is uncharged), the non-abelian nature of the flavour gauge group SU (2) demands that (W, Z) bosons must not only carry' flavour but also 'possess' this attribute, a feature directly manifested by its *triplet* structure in isospin.

The mathematical formalism for the interaction of non-abelian *SU* (2) gauge fields with matter was first proposed by Yang and Mills (1954)[15] as a generalization of the corresponding formalism for the (abelian) *U*(1) gauge field – the photon. Ostensibly it was meant for the understanding of the "strong" interaction among nucleons, but no physically viable (massless vector field) candidate with the correct *SU* (2) characteristics was immediately available. A few years later, with the production of vector mesons (rho, omega, phi) in the laboratory, Sakurai (1961)[37] suggested that these mesons be employed for gauge invariant couplings of the different types of baryon "charges" (isospin, baryon number and hyper charge) and thus mediate their strong interactions. There the omega and phi mesons were to serve as appropriate abelian *U* (1) fields carrying baryon number and hypercharge respectively while the role of the non-abelin *SU* (2) isospin field was to be played by the isospin triplet rho-meson. In a similar way, the isotriplet *W*-boson was proposed by Glashow (1961)[18] as another non-abelian gauge field to mediate the weak interaction. The difficulty with these proposals was the massive character of all these fields which stood in the way of "gauge field" intepretation. The mechanism through which this difficutly was subsequently overcome is discribed in Sec. (7).

6. SU (3) Color Charge : Glueballs

We are now in a position to describe how the gluon field mediates the strong interaction among quarks through the non-abelian gauge coupling mechanism. The "charge" in question is now the three-fold color attribute corresponding to the *SU* (3) gauge group, as a simple mathematical generalization of the *SU* (2) flavour group encountered in the foregoing. The non- abelian character of the *SU* (3) color group requires, as in the *SU* (2) isospin case discussed above, that the carrier group field (the gluon) must also "possess" the color attribute. The color multiplicity of the gluon field is indeed quite rich *an*, *octet*, as the self-adjoint *SU* (3) generalization of the corresponding triplet representation for an *SU* (2) gauge field (see Sec. 7). The massless character of the gluon field further ensures that gauge conditions are formally satisfied, thus hopefully ending the half-century old search for an appropriate strong interaction mechanism within the precinets of (gauge) field theory. The theory which has been named *Quantum Chromodynamics* (*QCD*), is closely patterned after *QED*, its electromagnetic countrerpart but, with a far bigger 'operational' responsibility. For, while QED allows electrons (or other charged particles) to be observable as free particles (if they have enough energy to overcome binding effects), QCD was purposely designed to account simultaneously for *two* major observational features which distinguish the behaviour of quarks from all other known particles, viz *assymptonic freedom* at short distances and permanent *confinement* at long distances[38]. As noted already (Sec. 4). the requirement of confinement stems directly from the failure to observe a "free" quark, while 'asymptotic freedom' stands for a continual weaking of the force due to the color charge as a pair of quarks approach each other indefinitely close (i.e., with asympotically higher and higher energies). As extensive calculations show, QCD already accounts for the short distance behaviour extremely well, but the confinement (long distance) feature is still only qualitatively understood.

Apart from a lack of quantitative understanding of "confinement" in terms of QCD (despite partial successes of lattice gauge theories[38]), the concept itself raises more fundamental questions. In this respect the question of a finer distinction as to the precise entity that is confined—the quark or the color attribute—is largely irrelevant since the quark is inseparable from its color attribute. Now if color is merely a confined attributte, what kind of experimental manifestations if any, should it have? (for if it were "hidden" a concept as to be totally inaccessible to all possible experimentation, it would have only academic value). There are two traditional signatures of color, one low energy and another high energy. The low energy process $\pi^0 \rightarrow 2\gamma$ which has been precisely measured, would be predicted too slow (by a factor of three) with respect to measurement, but for the color effect which just saves the situation. The high energy process concerns the rate of hadron production in electron-positron colliders, which again would require the theory to have the color degree of freedom contributing a factor of three) to match the data.

Still another type of manifestation of *pure color*, even without the accompanying quarts, is the (hitherto theoretical concept of *glueballs*[39]. A glueball is a bound state of two gluons (no quarks !) which has net color charge zero, so that it should be observable as an ordinary *hadron*, for example in the decay of a J/ψ particle ($\psi \rightarrow (gg) + \gamma$). This is a rather startling prediction, since no conventional "material" particle, such as the quark, is involved in the two-gluon system which, according to the confinement theory, should behave as a self-supporting, hadron-like, bound state. It is as if one were talking abont a two-photon bound state, which however is impossible since QED does not have any *confining* mechanism within its strucrure. In contrast QCD possesses precisely such a mechanism, so that the observation of a *glueball* with the experimental signatures (spin-parity, relative amplitudes for production and decay) should provide a dramatic test of the basic theory. Though such signatures are hard to disentangle from other hadronic backgrounds, two such candidates have been reported during the last couple of years[40], one of which (the pseudoscalar "iota" state) seems to have a fair chance of survival. Other predictions are three-gluon (ggg) and mixed-quark-gluon $(gq\bar{q})$ states which can in principle be colorless and hence observable as hadrons. An unambiguous identification of one or more of such particles would constitute a remarkable event, as it would confirm one of the most important distinctions between QCD and its parent theory (QED), concerning the nature of the relation between the "charge" associated with an interaction and the particle which mediates that interaction. States formally, this relation is abelian U (1) in QED, by virtue of which the photon is merely a carrier of charge but does not "possess" it. It is non-abelian SU (3) in QCD which requires the gluon not only to carry color charge but also possess it in a confining fashion. It is this last feature that gives rise to hadronic *glueballs* as one of the many manifestations of a non-abelian gauge theory.

7. Spontaneous Symmetry Breaking (SSB)

In the entire discussion so far we have tended to take rather for granted an implied underlying role of "symmetry" in the evolution of major theoretical ideas, while avoiding a formal definition of the word (in the hope that its use where necessary in context would serve the purpose of conveying its intended meaning as well). For a basically non-technical discussion, this may be permissible as along as the "symmetry" concerned is preserved, but requires some elucidation in a situation where a violation of this property is enuisaged.

Symmetry is meant here as an expression of invariance of physical laws w. r. t. arbitrary variations of the different 'coordinate system' in terms of which these laws find mathematical expression as "equations of equations" derived from a suitable "Action". Therefore a particular "type of symmetry is said to be preserved if the Action is invariant (and hence also the form of the equation of motion) w.r.t. the variation of the coordinates corresponding to that "type". Such an invariance in turn implies the conservation of a certain physical attribute characterizing that system. (This statement goes by the name of Noether's theorem)[41]. Thus translational invariance is associated with conservation of total energy-momentum, Lorentz invariance with that of total angular momentum and so on. In particular, invariance w.r.t. 'gauge' transformations of fields (regarded as generalized coordinates in a suitable Hilber space) corresponds to the conservation of charge of a particular "kind". Such conservation holds even in the presence of interaction of matter fields possessing such charges, to appropriate 'carrier' fields, in a guague-invariant manner; thus ensuring the preservation of the corresponding symmetry groups. In the foregoing we have encountered three such gauge groups, electric charge U(1), flavour charge or isospin SU(2) and color charge SU(3). Of these, the electric charge U(1) and color charge SU(3) are exact gauge symmetries since the corresponding gauge fields (photon and gluon) are *massless*. On the other hand, since the flavour SU(2) group has a massive gauge field (W±Z) associated with it[18], the corresponding charge would not be conserved in the usual course, since the mass terms of the carrier field would now destroy gauge invariance.

The solution to this problem has roughly a ten-year-old history, in which ideas were freely abstracted from parallel developments in solid state physics (superconductivity, superfluidity, tunnelling) culminating in the concepts of degenerate vacuum[42], Spontaneous Symmetry Breaking (SSB)[43] and the Higgs mechanism[44]. Now the. concept of a *degenerate vacuum* marks a sharp departure from the 'normal' situation in which a unique vacuum state, as the state of lowest energy of a given physical system, is usually taken for granted for obtaining the *solutions* to the field equations of motion. For, as long as there is a unique vacuum, not only do the equations of motion but also their solutions obey a given symmetry, such as is the case with U(1) charge or SU(3) color gauge groups. However, if the vacuum is degenerate, i.e. if there is more than one state of lowest energy, it is possible to have symmetry-violating *solutions*, while still maintaing exact symmetry at the level of the equations of motion (or equivalently the "Action"). Such a situation is called *Spontaneous Symmetry Breaking* (*SSB*).

To illustrate the meaning of SSB consider the trivial problem of road conventions adopted by different countries (*left* in India, U.K., ...; *right* in USA, Japan, ...). In principle, both conventions are allowed—and this feature corresponds to the 'equations of motion' maintaining their 'symmetry', —, but once a particular convention was adopted as a solution (long before the days of heavy traffic), the (left-right) 'symmetry' was 'spontaneously broken'.

As a less trivial example, consider two vessels shaped as in figs. 1 (a, b) each symmetrical about the vertical axis. A particle moving in fig 1 will settle down at the lowest energy point A, which is also the symmetry

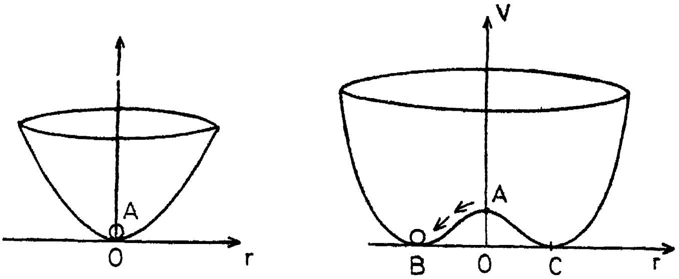

FIG. 1. Symmetric potential wells as models for vacuum structure. (a) A unique minumum at A ($r = 0$) corresponding to the normal vacuum; (b) a circle ($r = a$) of minima at B, C, ... corresponding to a degenerate vacuum.

point. (This corresponds to the normal situation of a unique vacuum). A particle moving in fig. 1 (b) on the other hand, may be (temporarily) balanced on the symmetry point A, but will eventually roll down to a position (B, C, ...) of *lower energy*, which lies on the circle of contact with the ground ($r = a$). This corresponds to the case of the degenerate vacuum since *any one* of the infinitity of points on this circle is as good as any other. However, once a choice has been made (say B or C), the 'symmetry' is 'spontaneously broken'. The position of lowest energy is no longer one of $r = 0$ but rather a *non zero* value $r = a$. The field theoretic analog of this statement is the following. For a 'normal' vacuum, the vacuum expectation value $<\phi>$ of a field variable ϕ is $<\phi> = 0$, corresponding to a unique lowest energy (c.f. fig. 1 (a)). For a degenerate vacuum, the analogous quantity for minimum energy is $<\phi> \neq 0$, corresponding to an arbitrary choice of the lowest energy state (fig 1 (b)). This non-zero value of ($<\phi>$), which has the physical dimension of mass, underlies the generation of gauge boson masses through the Higgs mechanism.

7.1 *The Higgs Mechanism*

According to a theorem due to Goldstone (1961)[42], a massless scalar field must accompany a degenerate vaccum—the Goldstone boson. This concept is known to occur in physics, e.g, as 'phonons' in superfluid helium, or 'magnons' in spin-glasses. However, such particles have not been observed in particle physics (except perhaps for the suggested 'pion' which does not quite fit the bill). To circumvent this problem, Higgs (1966)[44] suggested an alternative approach which may be best illustrated by the following simplified model. Consider the gauge invariant coupling of a matter field with a gauge field W_μ corresponding to a mere U (1) charge. If the vacuum is degenerate this feature may be brought out by a self-interacting scalar field, with a potential shaped as in fig. 1 (b), and also having a U(1) charge coupled to the same gauge field W_μ. At this stage, the gauge field is massless, so the 'Action' satisfies gauge invariance. However, since the vacuum is degenerate, the quantity $<\phi>$ is now *non-zero*, for reasons explained above. Using the translation $\phi = <\phi> + \phi'$, the new field obeys the normal vacuum condition $<\phi'> = 0$ (by construction) but the original (gauge) symmetry has now been lost w. r. t. the *new* vacuum. (In fig. 1 (b) this corresponds to shifting the origin from the symmetry point A to one of the *non-symmetry* points B, but nevertheless of lower energy). Further, the quantity $<\phi>$ would now appear all over the place in the new "Action", contributing several additional terms, one of which would correspond precisely to the mass term of the W-field, even though the old "Action" could not afford such a term (to conform to the guage principle). The Goldstone boson is now absent since the new vacuum has been made 'normal' through the origin shifting device, and the situation is as if the Higgs field has 'eaten up' the Goldstone boson to provide the (much needed) mass for the W-field.

This celebrated *Higgs mechanism* was exploited by Weinberg (1967)[19] and independently by Salam (1968)[19] to generate masses for the gauge fields (W±Z) mediating the flavour SU (2) interaction. The Salam-Weinberg theory was formulated in interlinked fashion for the SU (2) and U (1) gauge fields, thus putting on solid foundation the basic similarity of the Weak interaction mechanism with that of the electromagnetic. This *unified electroweak* theory was moreover found to possess the property of renormalizability (t′ Hooft 1971)[45] after which a spurt of activities through the seventies revealed wide-ranging agreement with many of its predictions culminating in the recent discovery (1983) of both the W and Z^0 bosons at the predicted masses[20]. (Its other prediction—the Higgs boson-still remains elusive).

8. Unification, GUT and Proton Decay

The *unified* nature of the electroweak theory (as between the e.m. and weak interaction) opened up the exciting possibility of still further unification on similar lines, especially with the strong interaction which is also mediated by gauge bosons (the gluons), the common feature among all the three fields being their *Vector* character. Indeed, the spectacular experimental success of the electroweak theory has been directly responsible for feverish theoretical activities in the direction of such "grand"unification[46,47] over the past decade. At this stage it is necessary to ask about the possible experimental signatures of such unification. The path to this is long and arduous, but the final goal is challenging—the proton should decay.

To get a clue to the reasoning, consider the electroweak theory first: how should the "unity" between the e.m. and weak interactions show up ? According to the Renormalization Group Theory of Coupling constants, the answer lies in their respective behaviour as a function of energy. At "low" energies ($<$ 1 GeV) the weak coupling constant, when measured in proton mass units, is only about 1% of the e.m. coupling constant α ($= 1/137$). This difference is a manifestation of the spontaneous symmetry breaking of the weak interaction at low energies. However at high enough energy ($\lesssim$ 100 GeV), whose scale is set by the order of magnitude of the W/Z mass, the full electroweak gauge symmetry termed SU (2) × U (1) is restored, and the weak coupling constant catches up with the electromagnetic, so that above this energy these two interactions are of *equal strength* and hence indistinguishable. Indeed the discovery of W/Z bosons at the expected masses constitutes an important check on this assertion.

If the same idea of unification is extended further to include the strong interaction characterized by the color SU (3) gauge symmetry, then one should expect the electroweak coupling constant (α_{EW}) eventually to catch up with the strong coupling constant (α_s) at a still higher energy. Estimates again on the basis of the Renormalization Group Equations[48], suggest that this super energy should be around 10^{15} GeV, only a few orders of magnitude short of the Planck mass ($m_p{\sim}^{19}$ GeV). At present, as well as in the foreseeable future, such energies are totally inaccessible to the biggest accelerators in the world (whose maximum possible output with the present day technology is not likely to exceed 10^5 GeV at the most optimistic estimates)*. However, the energy above which all the three fundamental forces would merge together and become indistinguishable, represents a most challenging theoretical concept—a "grand unified theory" (GUT). It sets a new mass scale $M_X(10^{15}$ GeV) as a direct generalization of the concept of the W-boson mass ($M_W{\sim}10^2$ GeV) above which only the electroweak forces unify. The precise value depends on the particular (group theoretical) model of unification chosen, but most models are consistent with M_X in the 10^{15} range.

It should be of interest to enquire into the meaning of this new mass scale. Since by the very nature of its introduction it symbolises a synthesis of the lepton and quark degress of freedom, it must carry the quantum numbers of both. In other words, it is a *lepto-quark* (X) boson. Gauge theories have been constructed along the lines of electroweak theory wherein such X-bosons mediate the GUT interaction among quarks and leptons in a highly degenerate vacuum at energies above 10^{15} GeV, in much the same way as the SU(2) × U(1) bosons (γ, W, Z) mediate the electroweak interaction among quarks and leptons above 100 GeV. As the energy is lowered Spontaneous Symmetry Breaking now causes the X-boson to acquire a huge mass (M_X) via the Higgs mechanism just as the W/Z bosons acquired their respective masses (M_W). The mass M_X represents the next milestone in the march towards unification, above which no distinction should exist between the strong and electroweak coupling constants. A schematic diagram is shown in fig. 2.

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* The diameter of such an accelerator would correspond to the radius of the moon.

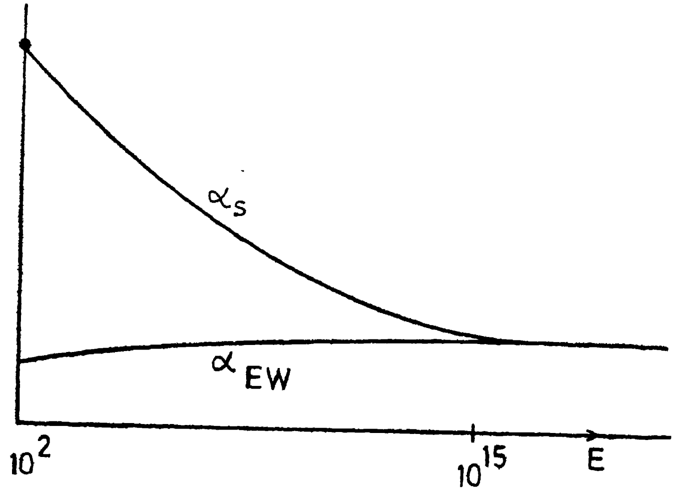

FIG. 2. Schematic diagram illustrating the variation of strong and electroweak coupling constants with energy within the Renormalization Group Theory. They merge together above 10^{15}Gev in GUT models.

What should be the low energy experimental manifestation of this new mass scale which is far beyond present-day accelerator capacity ? Because the X-boson connects the leptonic quantum numbers with the hadronic, the instability of the proton against decay into lighter particles, is logically predicted (Pati-Salam 1973)[46], though the enormous gap between the proton mass and the X-boson mass would greatly inhibit the process, much like the Gamow barrier penetration effect in α-decay. (The "barrier" in this case is the mass M_X, which is much too high for the proton mass, thus indicating the nature of the analogy).

What distinguishes proton decay from other known processes is that unlike the latter which conserve baryon number (B), *and* separately the lepton number (L), this extraordinay process violates both. In a class of models based on the GUT concept, the X-boson mediates the basic transition $qq \to q\ \bar{l}\,(\bar{q}$ = quark, l = lepton, bar = antiparticle) which causes the proton to decay, e.g., into an $(e^+\pi^0)$ pair through the mechanism shown in fig. 3, as one of many possible modes. In this class of models[47], one still has the conservation of B-L, implying that the traditional "class distinction" between baryons and leptons must break down due to the possibility of interconversion at super high energy ($\sim 10^{15}$ GeV). Only a faint signal of this effect is in the form of proton decay. The signal is so faint that the expected lifetime ($\lesssim 10^{31}$ years) is much longer than the age of the Universe itself.

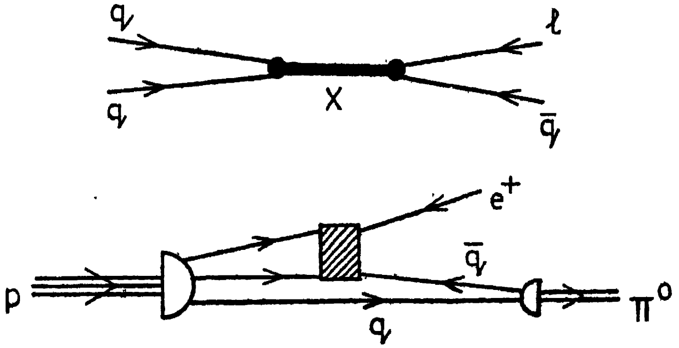

FIG. 3. Proton decay mechanism in GUT models; (a) Basic Interaction $qq \to \bar{q}\bar{l}$ through X-boson exchange (thick line) responsible (fig 1 b) for the decay mode $p \to e^+\pi^0$ through the basic interaction (a).

This dramatic prediction has (understandably) generated a world-wide experimental activity for detecting this remarkable phenomenon. Needless to emphasize, the detection machinery must be extremely fine tuned to eliminate all possible background effects to catch this faint signal. For such reasons, such experiments must be planned in the deep underground. Even so, they would not be immune to the cosmic neutrino flux, the elimination of whose background effects in the detection of such a process is a major experimental task. The Kolar Gold Fields (KGF), where deep underground cosmic ray experiments have had a long history, has been the first venue for this experiment under an Indo-Japanese collaboration[49]. Subsequently similar experiments have been intensely under way in Europe (NUSEX)[50] and America (IMB)[51]. The overall outcome is so far negative, thus implying that the time of decay, if at all finite, is probably much larger than the original theoretical estimates ($10^{30\pm1}$ years) on the basis of which the detecting devices had been set up, though it is unlikely that the limits of detectability (taking account of the neutrino background) can catch up with a life time much larger than 10^{32} years[52].

9. The Monopole : A New Pathology of SSB

Another aspect of proton decay that has unexpectedly come up during the last two years is the so-called Rubakov[53]-Callan[53] (1981- 2) effect which predicts that if an SU(5) *t'*Hooft-Polyakov Monopole[54], passes through nuclear matter, it would induce proton decay at a rate comparable to *strong interactions,* which would be a far greater "catastrophe" than the residual GUT-interaction effect described above.

Now the theoretical basis of the *Monopole* concept dates back to 1931 when Dirac[55] first studied the implications of an isolated magnetic charge akin to the electric charge which had never figured in the electromagnetic context due to a total absence of its observable effects. Indeed, Dirac could turn this argument around to show that for an isolated magnetic charge, or "monopole" not to reveal any observable effect the strength (g) of its "charge" and the unit of the electric charge (e) must be related by a quantum condition;

$$eg = nh \quad (n = \text{integer}). \qquad \ldots(6)$$

Historically this was the first suggestion for a possible mechanism for electric charge quantization. (This problem was studied from a different angle by MN Saha[56] in 1936). Related with the quantization aspect, eq (6) suggests that the Monopole charge g, as the reciprocal of the (small) electric charge e, would have to be particularly large, even for $n = 1$, which partly explains why the force due to a magnetic charge with matter could in principle be very strong (unlike the electrical force).

Now, while the physical applications of the Dirac Monopole have been hindered by certain mathematical problems of singularity near its location ($r = 0$), the basic concept got revived from another unexpected angle in the last decade with the discovery by t' Hooft and Polyakov (1974)[54] of the existence of similar objects (but without singularity problems at $r = 0$) arising out of spontaneously broken gauge symmetries. These finite energy Monopoles seem to be a natural fallout of Spontaneous Symmetry Breaking in most gauge field theories (except the electroweak SU(2) × U (1) within the same theoretical framework that causes gauge bosons to develop their masses (M_W, M_X). In particular a Monopole must be an integral part of the same gauge theories — the GUT's — which predict proton-decay through a very feeble interaction. However, the Monopole itself has a "strong" interaction with the proton (for reasons given below eq (6), so that even the presence of a single Monopole in the vicinity of matter would cause a "fast" decay according to theory. If this effect is taken literally, the absence of proton decay events in the deep underground laboratories should be construed to set effective *upper bounds* on the Monopole flux invading Mother Earth. For *if GUT* happens to be the physically correct theory, there would be no logical escape from such monsters which must have been produced right at the moment of the Big Bang during the earliest phase of cooling (when GUT symmetry broke down to the electroweak stage), unless their total number was below the danger level. Alternatively, GUT may *not* be the final word for the unification scenario, a more likely proposition.

10. Towards further Unification : Boson Fermion Symmetry

No description of particles and their interaction would be complete without the inclusion of gravitation which dates back to Newton. Einstein's geometrical formulation of the gravitational field (within the framework of his General Theory of Relativity)[57] has preserved it as a class by itself, not only in its mathematical elegance and profundity, but above all as the physically most acceptable theory of gravitation even to-day. Attempts at Unification of gravitational and e.m. fields since the twenties have not yielded results. Perhaps the geometrical space time structure of this field calls for an entirely different strategy for unification from the "gauge" techniques employed so far for the electroweak and strong interactions. In more physical language the "gravitational charge" which is presumably associated with space-time curvature seems to be on an aprioi different footing from the other kinds of charges (e.m. flavour, color) whose conservation implies certain symmetries in internal space brought out by the grauge principle. However, one would be apt to enquire about the nature of "internal" space in which these symmetries arise, since such space is distinct from ordinary space-time. One possible speculation is that perhaps one is dealing here with an extension of ordinary space-time, where the extra dimensions have compactified to a very small size which cannot be probed at ordinary energies, but show up only as the "gauge" manifestations of different "charges". Indeed such a possibility was suggested as early as the twenties by Kaluza (1921)[58] and Klein (1926)[59] in their attempts to unify gravitation with electromagnetism. They postulated a *fifth dimension*, whose conjugate momentum would be electric charge, but whose *size* would be of the order of Planck length ($G^{1/2} \sim 10^{-33}$ cm), while the masses of all charged particles would be in units of the Planck mass ($G^{1/2} \approx 10^{19}$ GeV). This idea may sound too unrealistic in terms of the actual detail of to-day, but with appropriate extensions, the Kaluza-Klein approach is being vigorously pursued on an almost industrial scale[60], in accordance with the belief shared by a certain school of thought that *seven extra dimensions*, added to space-time, should prove adequate for uniting gravity with electroweak and strong forces. At the moment it is a completely theoretical approach with no observable signatures in sight.

A different kind of theoretical approach with a similar long term goal of uniting gravitation with other forces has come from an entirely new principle — *Boson Fermion* Symmetry or *Super Symmetry*[61,62] (SUSy). So far Bosons and Fermions have been regarded as two distinct classes of particles genetically unrelated to each other. But just about a decade ago a new symmetry principle-Super Symmetry or SUSy was proposed (Wess-Zumino 1973)[62] wherein these two classes of particles were sought to be interlinked to each other through a new kind of transformation, which would convert bosons into fermions and vice versa, but the total 'Action' wouldstill remain invariant. These special tranformations would now have to act in an extended space in which the space-time varlables are augmented by certain 'spinor' variables which 'anti commute' with one another. Apart from exhibiting an extremely rich and elegant mathematical structure, the new theory has a most important property of great potential value for physics viz, Renormalizability for high spin systems. In particular, an interacting gravitational field (spin 2) is now renormalizable, thus removing a major obstacle to its quantization (hitherto plagued by all sorts of infinities inherent in the quantum formulation). This new facility has paved the way to possible unification of gravity with the other three forces, a supergravity theory.

In recent years, the tempo of theotetical activities in SUSy and supergravity has reached dizzy heights[63]. The theoretical movement seems to have generated a momentum of its own with a continuing development of a new kind of mathematics (fascinating in itself) with no corresponding concern for *observable* consequences at the more down to earth level of physics.

Now (from the point of view of the very scope of this article) a major observational consequence of the new principle of Boson Fermion Symmetry (SUSy) is a virtual *doubling* of the number of elementary particles, since each particle or field of the 'conventional' type now requires a "SUSy partner". Thus each conventional boson must have a fermion SUSy partner carrying identical 'charges' and vice versa. For example, the photon's SUSy partner would be a spin $\mp \frac{1}{2}$ (charge neutral) partner as the *photino*; a gluon's SUSy partner would be a (colored) spin $\frac{1}{2}$), *gluino*, and so on. Likewise, a lepton's SUSy partner would be a spin-0 lepton (called Slepton), a quark's SUSy counterpart a spin-0 squark etc.[64].

Table 2 gives a list of SUSy partners of the more established particles, together with their 'names' and quantum numbers. Because of the (expected) spontaneous breaking of SUSy, most of these partners would acquire (generally high) masses. Such a multiplicity of particles poses a formidable experimental problem of their detection (should they exist at all). Of these, the gluinos and squarks have color charges and would therefore be "confined". These should be looked for only in terms of colorless hadrons (or "hadrinos"/"shadrons") that they can form in association with normal gluons and/or quarks. Since plenty of colorless combinations are possible, further guidelines are needed for a more systematic investigation, starting from the lowest mass "hadrino" states. (Possible low-lying candidates are $\tilde{g}g$ and $\tilde{g}qq$,). Unfortunately the inability of the theory to predict firm theoretical

TABLE 2 : *SUSY Partners of known particles*

Particle	*Spin*	*SUSY Partner*	*Spin*
Photon (γ)	1	Photino ($\tilde{\gamma}$)	$\frac{1}{2}$
Lepton (l)	$\frac{1}{2}$	Slepton ($\tilde{l}$)	0
[e, μ, τ]	$\frac{1}{2}$	[$\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$]	0
neutrino (ν)	$\frac{1}{2}$	seneutrino ($\tilde{\nu}$)	0
quark (q)	$\frac{1}{2}$	squark ($\tilde{q}$)	0
[u, d, s, c]	$\frac{1}{2}$	[$\tilde{u}$, $\tilde{d}$, $\tilde{s}$, $\tilde{c}$]	0
gluon (g)	1	gluino ($\tilde{g}$)	$\frac{1}{2}$
W-boson (W)	1	Wino ($\tilde{W}$)	$\frac{1}{2}$
Z-boson (Z)	1	Zino ($\tilde{Z}$)	$\frac{1}{2}$
Higgs (h)	0	Higgesino ($\tilde{h}$)	$\frac{1}{2}$
Goldstone	0	Goldsino	$\frac{1}{2}$
Graviton	2	Gravitino	$\frac{3}{2}$

(and so on)

bounds on the expected masses of these new particles as well as their decay patterns, to motivate more quantitative experimental efforts for their detection, is a major stumbling block to further progress[65].

At the moment, super symmetry is a "theoretical theory" but has nevertheless been involved in the prediction of a rich crop of new heavy particles. So far none has been "seen" even remotely, but the stakes are high either way. Just as the detection of even a single SUSy particle will give a great boost to the theory in its onward march towards the understanding of ultimate matter, a continued lack of experimental support would presumably call for an agonizing reappraisal of the theory.

11. A Fourth Stage of Compositeness ?

A simple counting of the contents of table 1, taking account of the color degrees of freedom which give a further multiplicity of *three* for quarks (and antiquarks), and *eight* for gluons, already gives nearly half a century of "elementary" particles. And if the Boson-Fermion Symmetry—so far a theoretical cocept—is also taken into account, table 2 augments this list by another factor of *two*, making up an impressive tally of a century. Are all these particles really elementary ? Clearly the situation is strongly reminiscent of the one existing in the early sixties (see Sec. 1) when the appearance of an enormous number of baryons and mesons and their 'resonances' had led to the *quark* proposal which provided quick relief through a natural understanding of the vast complex of hadron structures in terms of a few (3) basic entities. And with the successive successes of the quark model it did not seem to make the least difference whether quarks had been explicitly "seen" or not.

Are we heading for a similar situation again after 20 years ? For, apart from the general considerations of economy of description, the three-tier family structure of quarks and leptons (see Table 1) would be a pointer towards a further substructure in tune with the lessons of history. There is an important qualitative difference however from the pre-1964 situation which had been the result of an impressive array of *experimental* data with periodic structure strongly suggestive of compositeness. The present situation on the other hand is more a result of *theoretical initiative* (at best not in disharmony with data), than dictated by purely experimental compulsions. The reason is not hard to seek. The hadronic substructures that were being discovered in the fifties and sixties were well within the probing capacity of the (then upcoming) accelerators which had just started "looking up" on the energy scale. Accelerator technology has since developed several-fold, making it possible to "manufacture" in the laboratory particles of such undreamt of masses ($\sim$ 100 GeV) as those of the W and Z bosons, but the challenges posed by postulated sub-structures of quarks and leptons, in terms of the sheer dimensions of experimental data needed to throw meaningful light on theoretical conjectures are far greater than experimental capacity. For, the point structures of leptons and quarks are already *experimentally* established to better than 10^{-16} cm resolution, almost saturating the proble capacity of the most energetic accelerators of to-day, and a further experimental resolution is a minimum for testing the predictions on the sub-structures of these particles.

Thus it is unlikely that much higher energy experimental support would be forthcoming in the near future, either to confirm or to rule out, theoretical conjectures of quark and lepton compositeness. Nevertheless several composite or preon models have appeared in the literature during the past ten years [66–70] as an alternative scenario to Grand Unified Theories (Sec. 8) which are best described as efforts to find "bigger and better groups" in the quest for unification of particles and their underlying forces. In this respect the situation has been somewhat analogous to that of the early sixties when guessing at more and more elaborate group structures used to be a favourite pastime of theoreists to accommodate the vast multiplicity of accumulating hadronic data until the quark model came to the rescue. In the present situation any possible form of discrimination between *preon* and GUT models or among the substructure predictions of different preon models is unlikely to come from richer data emanating from the highest energy accelerators, failing which various (subjective) considerations such as simplicity, aesthetic appeal, 'naturalness of description' (with few assumptions), and perhaps even "lessons of history", would presumably play important roles. The data for quantitative comparison would be more likely to come from low energy precision experiments relating to quantities whose 'physics' is traceable to very short distances. Proton decay represents a classic example of this kind. At the very minimum, any respectable theory of quarks and leptons—preon or GUT or whatever—must not fail to provide simple and convincing accounts of their visible systematics especially (i) a recurring spin — $\frac{1}{2}$ structure for three successive generations, (ii) mysteries of the generation structure which makes the 3 families look so alike and yet such jealous guardians of their respective identities and (iii) a steeply rising mass pattern for the successive generations.[70]

Preon models proposed so far fall into two broad classes : (A) Models in which the preons are basically synonymous with certain chosen attributes of the composites themselves[66,67,69]. In such models the constituents (preons) do not have any independent status other than the respective degrees of freedom they are intended to convey, e.g., a "color" for the color index, a "flavon" for the flavour index, and so on. To that extent such models tend to pre-empt a dynamical understanding of these composite attributes from the deepest level of preonic interactions.

(B) Models in which preons play a role more akin to nucleons in nuclei or quarks in hadrons, so that such constituents are recognized to have an existence independent of the attributes they are supposed to possess[68,70]. Such models do have the potential to provide a dynamical understanding of one or more of the composite attributes in terms of interpreon forces, without having to postulate all of them (color, flavour, generation) as fundamental.

It is not in the scope of this article to describe the detailed working of these models, except that class B models have, on the whole, proved somewhat more promising for an eventual preon dynamics underlying the quark and lepton substructure, so as to facilitate a composite model calculation of their masses and other physical characteristics[70]. The scenario envisaged in such a description would closely parallel these encountered in the three earlier stages of compositeness, especially the quark stage for hadrons, with an analogous feature of confinement, but on a vastly different scale of operation (10^{-16} cm compared with 10^{-13} cm for color confinement). This would call for a new fundamental force—call it "hyper color"—mediated by say, "hydergluons" which would keep the hypercolor "charge" *confined within* 10^{-16} cm to account for the point-like structures of quarks and leptons. This is a most stringent requirement, one which must surmount several theoretical barriers for an acceptable, mathematically self-consistent, theory. And if at all such a theory emerges, it will have to pass several "experimental tests" (listed in the foregoing) not necessarily of the high energy type. It is a distant goal but the stakes are high, especially because history is unmistakably on its side.

12. Cosmological Signatures of Particle Physics

In parallel with the frantic researches on GUT's and preon models, supersymmetry and supergravity, there has been a very active confrontation between particle physics and cosmology, which has been particularly noticable since the last decade. Astrophysicists use new ideas in particle physics and in return their analysis often provides valuable constraints on these very ideas. This two-way traffic between microphysics and macrophysics which perhaps represents the biggest challenge for science as a whole, has been occasioned by major strides in both fields. Landmarks in particle physics have been outlined in the foregoing sections which suggest that a strong consensus has indeed evolved in the form of the Standard Model for the weak and e.m. interactions and QCD for the strong interaction between quarks and gluons, the common underlying theme being the *gauge principle* for different types of interactions. The still bigger unifying principles of GUT, SUSy etc. may be regarded as attempts to deal with further unanswered questions such as those bearing on the number of quark and lepton families and their mass patterns, the mechanism of merging of electro-weak and strong interactions at very high energies, and so on. Unfortunately the limitations of accelerator technology have necessitated a heavy reliance on the speculative element, especially in respect of the very massive particles that have been predicted (e.g., the X-boson). This is precisely where cosmology has come to the rescue as an exponent of the Big Bang Model of the early universe which has been described[71] as an ideal high energy laboratory for the particle theorist.

The logic of approach to particle physics via cosmology is as follows[72]. During the early evolution of the universe, following the Big Bang, the temperature and density were very high and collisions were very frequent, so much so that a variety of particles were produced during the early phase and equilibrium was established through rapid interactions among them. The particles involved during this epoch were just of the types which (i) are hard to produce in the terrestrial laboratory since they are too massive or (ii) are difficult to detect because they interact too weakly. Indeed from the theorist's point of view, the Big Bang was Nature's ideal accelerator not subject to the budgetary restrictions which plague experimental particle physics of today.

As the universe expanded and cooled, the reaction rates could not keep up with the rate of expansion so that 'particles' of various kinds dropped out of the equilibrium configuration, leaving behind 'relics' of those early epochs. The masses, lifetimes and interactions of these early particles determine, according to standard theoretical models, their relative survival rates as well as the manner in which they presumably influenced the subsequent evolution. In this sense, these relics represent the "tools" of cosmology for probing the principles of particle physics. For example, since long lived particles surviving from the early universe are expected to be present even to-day (anomalous nuclei, free quarks, stable leptons, etc), negative results in their searches would imply severe constraints on the very theoretical foundations on which such expectations are based. Similarly because of the universality of gravitation, such long lived particles will contribute to the present cosmological mass density ρ_0 whose observational limits ($\lesssim 2\times10^{29}$ gm/cm^3) in turn lead to significant restrictions on the masses of the neutral and charged leptons.

Still another probe is provided by primordial nucleosynthesis. In particular, the primordial abundance of ^{4}He depends sensitively on the competition between the rate of weak interaction and the expansion rate. The latter depends on the number of 'flavours' (or generations) of 'neutrinos' present at a certain temperature stage (T $\sim$ 1 MeV) in the evolution of the universe, thus providing severe limits on this number itself.

Now to get near the moment of the Big Bang (on a logarithmic time scale) implies a huge extrapolation in time of the presently expanding Hubble flow of distant objects in the universe, to the epochs when the matter in the universe was much denser and hotter than it is to-day. The physics of such extropolation is facilitated through the use of the cosmological principle of isotropy and homogeneity on the one hand and General Relativity on the other[73], which in principle have the theoretical ingredients for leading all the way to the Planck epoch (t_0) when the energies of the particles in the universe where $\sim 10^{19}$ GeV. Such energies at which gravitational effects were important are estimated to have been attained for the first t_0 ($= 10^{-43}$) *seconds* after the Big Bang, after which the universe would have cooled as it expanded. An important landmark during this long journey backward in time from the present to the Planck epoch is one when the universe was some 1000 times smaller (and hotter) than it is to-day, and consisted of ionized matter only. The 3°K microwave background radiation which now permeates the entire universe is believed to be a relic of this particular epoch (say Epoch I), having escaped when the universe cooled out of the Epoch I, causing the ionized nuclei and electrons to combine and form the neutral atoms that populate the universe to-day. At a still earlier stage, say Epoch II, when the universe was a billion (10^9) times smaller (and hotter) than it is to-day, a large fraction of matter ($\sim$ 25%) had already been turned into ^{4}He from neutrons and protons by thermo nuclear reactions, along with smaller amounts of tighter nuclei[74], and this gas had escaped during the process of cooling from Epoch II to Epoch I. The latter is indeed evidenced from the observation that as much as 25% of the matter in the universe exists in the form of ^{4}He, while only a few percent could have been manufactured in stars.

As a result of the 'observational successes' of the above two extrapolations through Epoch I to Epoch II, physicists have been encouraged to continue such extrapolations back to Epochs III, IV and V, the last (Epoch V) of which was $\sim 10^{18}$ times earlier (and smaller) than the present one when typical particle energies were $\sim 10^{15}$ GeV. This is precisely the energy domain of the greatest concern for the particle physicist of to-day since it has a direct bearing on the speculations on grand and super unified theories of the two intermediate epochs. Epoch III represented the "time" when the universe was some 10^{12} times smaller (and hotter) than to-day and corresponded to the stage when the quark-gluon plasma made a phase transition to the familiar hadrons. (It is believed by some that perturbations and shock waves generated during this transition may have triggered the formation of galaxies[75]). While there are no direct astrophysical signatures of Epoch III, (unlike those of Epochs I and II quoted earlier), such a cosmological picture is nevertheless intimately linked with the very theoretical foundations of strong interaction physics whose observational successes are just too many to need further defence. Direct experimental tests of the quark-hadron phase transition are now on the threshold of feasibility in terms of high-energy heavy-ion accelerators. Similarly, Epoch IV which preceded Epoch III (above) by a factor of 10^2—10^3 in (inverse) size and temperature, corresponded to the stage when the standard unified model of weak and e.m. interactions gave way to their separate structures via Spontaneous Symmetry Breaking (see Sec. 7) caused by cooling As with the Epoch III, the impressive successes of the Glashow-Weinberg-Salam theory, should amply justify the extrapolation to Epoch IV, despite lack of a direct astrophysical signature.

The further extrapolation from Epoch IV to V (when the universe was 10^{16} times smaller and hotter than to-day) is at the moment a matter of intense theoretical speculation bearing on the current status of grand and super unified theories, with no direct observational evidence (terrestrial or astrophysical) available so far to throw light on them. Nevertheless some cosmological constraints bear indirectly on the status of some theories. Especially important is the sensitivity of cosmological nucleosynthesis to the *number* of particle species lighter than ~ 1 MeV whose thermal energy density must be fine-tuned to the observed ^{4}He abundance of 25% in the universe. This limits the number of neutrino-like species to *three* or at most *four*. This figure accords rather well with the 3-generation structure believed to exist for leptons and quarks, requiring as many neutrino species (see Sec. 2). (On the other hand, direct particle physics experiments in the Laboratory yield far bigger bounds on this number). Another cosmological constraint comes from the masses of such neutrinos' which, if stable, should be lighter than ~ 100 eV, in order that their mass density may not exceed the observational limits on the density ρ_0 ($\lesssim 2 \times 10^{-29}$ gm/cm^3) of the universe. Again, this limit is much more restrictive than the corresponding limits of terrestrial experiments ($\nu_\mu \leqslant 300$ KeV,

$\nu_\tau \leqslant 200$ MeV), even though recent indications of a rather light ν_e (≈ 30 eV) have been obtained[75].

One of the biggest theoretical questions concerns the possible mechanism responsible for the observed cosmological ratio $n_\gamma / n_B \approx 10^9$ for the number of photons to the number of baryons in the universe, and the fact of a strong asymmetry between matter and antimatter ($n_B \gg n_{B^-}$). In this respect GUT theories have acquired a good deal of creditility in so far as they facilitate synthesis of baryonic matter in preference to antimatter, in a manner first suggested by Sakharov[76]. The idea is that interactions which violate baryon number conservation as well as CP conservation, can take an initially symmetric universe into a state with more matter than antimatter as soon as they drop out of thermal equilibrium. This idea harmonises with a GUT mechanism which operates through the (non-equilibrium) decay of X-bosons. However this optimistic picture on GUT's must be balanced by some of their 'unpleasant' features, especially problems of reconciliation of conventional Big Bang models with too little monopole flux, so as not to catalyse proton decay too violently (see Sec. 9). More importantly, absence of proton decay so far in the laboratory has caused some unavoidable set-backs for GUT models. On the other hand, SUSy GUT models of the SU (5) type change the order of priories of pionic and kaonic modes[77] and do not yet seem to be ruled out by experiment.

To summarize, cosmology has provided important signatures of, and constraints on, current ideas on particle physics, as yet unavailable in the laboratory. However, in the absence of further experimental progress in the laboratory (monopoles, proton decay, etc.) the speculative element beyond Epoch IV (corresponding to the electroweak unification) remains much too large for comfort. In the meantime, the theoretical two-way traffic between particle physics and cosmology continues at a rapid pace.

13. Conclusion : Trends and Outlook

In the foregoing we have tried to present a panoramic view of the successive stages of elementarity of particles as these have emerged over the past sixty years. It has been a long journey from the atomic shell structure which offered the first formal understanding of Mendeleyev's Periodic Table. However, the lessons of the *Periodic* Table *and* of *Shell* structure have been repeatedly used in the chronological order to explore the successive stages of orderliness of particle behaviour, first through the Mendeleyevian concept of group structures followed by an appropriate compositeness ansatz characterized by shell structures (in terms of the constituents). Three such stages have passed and a fourth one is in the offing. In this process of unfolding, theory and experiment have gone hand in hand, the former with the tools of *symmetry* and underlying *unity* of physical laws, and the latter with an ever increasing energy scale of particle accelerators for probing shorter and shorter distances.

A true understanding of elementary particle structures is intimately linked with the knowledge of their mutual *interactions* (or forces) which represent the meeting ground of theoretical predictions and experimental probes. Though these forces have long been classified into four distinct types—electromagnetic, weak, strong and gravitational —, there has been a traditional tendency to discern an underlying *unity* in their manifestations. Indeed this trend is traceable to the days of Maxwell who successfully unified electricity and magnetism, and Einstein who dedicated his entire life to unification. Einstein's success should be judged *not* by his apparent failure to "unify" e.m. with gravitation, but rather by his signal contribution to the foundations of physics in providing an *integral* theory of gravitation linking the gravitational force with the very geometry of space-time. Gravitation has held its ground as a class by itself[57], despite efforts by the modern theoretical community to bring it in line with the other three kinds.

Leaving apart gravitation, the principles of gauge symmetry and gauge fields carrying generalized charges in an exactly conserved fashion, have lent a deeper meaning to the force concept as a big step towards their eventual unification. In particular, these principles have led to a deep and most satisfying connection between the weak and e. m. forces in the form of the *standard model*[19], probably just short of full unification (in the sense that electricity and magnetism are considered unified in Maxwell's theory). Perhaps the "fly in the ointment" is the aspect relating to Spontaneous Symmetry Breaking, which, though a profound physical principle with impact on several branches of physics, does not enjoy a matching theoretical formulation to meet the exacting standards of fundamental forces. And when it was stretched to the GUT level it was probably "overworked" (the hen that laid the golden egg?) already. Stated differently, there is a certain element of arbitrariness in the Higgs mechanism of mass generation whose impressive prediction for W, Z boson masses owes more to the (accurate but phenomenological) knowledge of the fermi coupling constant than to a genuine understanding of the underlying structure of the Higgs field.

On the other hand, the three cornerstones of theory—field unification, gauge principle and Renormalizability—all inherited from the parent theory of QED, have met with an unexpected degree of success (in the form of QCD) independently at the strong interaction level. Admittedly there are still formidable problems of reliable prediction of hadronic properties relating to the manifestations of QCD at non-asymp totic freedom energies, but these are regarded as more of a computational than of a conceptual nature. In particular, its characteristic prediction of confinement, a unique feature of non-abelian gauge fields, may well be on the verge of experimental confirmation through the *glueball* phenomenon. Perhaps it is not entirely a coincidence that the gauge symmetry is exact in this case, and "spontaneous symmetry breaking" does not enter this (QCD) sector of field theory.

Nevertheless, the theoretical trend continues to show an ever increasing urge for *unification* of the different forces (including gravity), a successful outcome of which will be a determining factor in the "understanding" of substructures (if any) of leptons and quarks. In this respect the decade old concept of Bose-Fermi (SUSy) Symmetry, with its vastly "liberalized" criterion for Renormalizability*, has come as a powerful tool for unification within the SUSy framework, but only at the cost of doubling of the existing number of "elementary" particles through their SUSy partners (table 2). From the point of view of the physics of particles, this feature must be particularly welcome since these partners represent the only observable signatures of an otherwise theoretical theory, thus making it formally vulnerable to experimental verdict. But alas (!), the ill-determined guidelines for the expected mass locations of the SUSy partners, thanks again to a heavy reliance on an (already overworked) SSB principle, has considerably queered the pitch for confrontation between theory and experiment.

For the moment it is sheer considerations of the aesthetic appeal and the mathematical beauty of a higher symmetry principle that have kept up the "faith" in the vast theoretical investment, Nevertheless there are some signs of contact with physics; viz. the influence of this new thinking has started percolating into the already established zones of compositeness of material structure (nuclear and hadronic) where fairly serious efforts are underway in looking for signatures of Bose-Fermi type symmetry among the existing nuclear and hadronic energy levels[78]. Since there is no dearth of accurate data in these zones of compositeness, they may offer a quick, albeit rather indirect verdict on the issue, which would still be a poor substitute for a direct test of the SUSy partners.

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* Facilitated by pairwise cancellation of otherwise strong infinities arising from virtual boson and fermion intermediate states.

Perhaps more important than the question of SUSy partners (or rather because of them, if they do exist) is the question of lepton and quark substructures. Since the contact with experiment will increasingly become less direct (since distances $\sim 10^{-16}$ cm almost saturate the direct probing capacity through high energy experiments of to-day) theoretical considerations and physical insight, together with reliance on accurate *low energy* data, will increasingly come into play. These may even require reappraisals of the theoretical foundations of the present day structure of quantum mechanics, some such attempts being already in evidence. For example, the hypothesis of a *fundamental length* (l_0) would lead to a "discretization" of quantum mechanics (which itself was the result of a first level discretization of classical mechanics)*. In the language of the field theory the existence of a fundamental length would be strongly reminiscent of Yukwa's hypothesis (1953)[80] of a non-local field theory based on a reciprocity or symmetry principle and 'momenta', symbolized by the structure of a harmonic oscillator, (vaguely analogous to the quality structure existing between electric and magnetic fields). Considering the variety of theoretical options available, the emergence of a physically viable and mathematically self-consistent composite theory of leptons and quarks may not be immediately in sight. However, if history is any guide, it strongly points to such a possibility in the long run.

At the present moment, High Energy Physics which still holds the key to the understanding of elementary particle structures, appears to be in a state of flux. This is especially true of theoretical efforts ; there is enormous activity in the field, but mostly centred around certain profound ideas espoused by a few important centres of theoretical culture, thanks to the vastly improved communication system existing to-day compared with a generation ago. Now such organized activity is indeed a necessity for high energy experimental physics, but it is not clear if a similar compulsion holds for theoretical investigations as well. For one thing, the "surprise element" in the evolution of ideas, which has always characterized the greatest discoveries in physics, seems to have disappeared in to-day's world of instant communication and fierce competition.

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* Discrete quantum mechanics of this kind has indeed been proposed (T. D. Lee)[79] and a recent comparison with low energy physics data suggests that such a length (l_0) if it exists at all should be $< 10^{-18}$cm.

Finally, it is tempting to ask if, granted that leptons and quarks do have preon substructures, the quest for elementarity ends there, or this successive unfolding of Nature's mysteries is an unending process. Stated somewhat differently, were "preons" the ultimate consituents present during the "Big Bang" or are they many-fold composites of the ultimate matter (let it be termed as Gamow's Ylem matter)[81] which exploded at that Great Moment? In this respect, it is interesting to note that Astrophysics as a discipline whose foundations had been solidly laid by such pioneers as Bethe, Chandrasekhar and Gamow, has in recent years come to be increasingly involved with the physics of elementary particles. On the other hand, astrophysical constraints on elementary particle behaviour are in general so weak that they leave too much scope for the speculative element. Therefore in practice astrophysical signatures have tended to be more confusing than illuminating. And what with the 'inflationary scenario' (and its annual versions), and fragmentation of space-time during the very early apochs (measured in 10^{-n} Sec, $n > 43$), perhaps the answers are forever buried deep in the cosmic oblivion.

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